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High uncertainty in 21st century runoff projections from glacierized basins

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ABSTRACT

Glacier response to a changing climate and its impact on runoff is understood in general terms, but model-based projections are affected by considerable uncertainties. They originate from the driving climate model, input data quality, and simplifications in the glacio-hydrological model and hamper the reliability of the simulations. Here, an integrative assessment of the uncertainty in 21st century glacier runoff is provided based on experiments using the Glacier Evolution Runoff Model (GERM) applied to the catchment of Findelengletscher, Switzerland. GERM is calibrated and validated in a multi-objective approach and is run using nine Regional Climate Models (RCMs) until 2100. Among others, the hydrological impacts of the RCM downscaling procedure, the winter snow accumulation, the surface albedo and the calculation of ice melt and glacier retreat are investigated. All experiments indicate rapid glacier wastage and a transient runoff increase followed by reduced melt season discharge. However, major uncertainties in, e.g., glacier area loss (−100% to −63%) and the change in annual runoff (−57% to +25% relative to today) by 2100 are found. The impact of model assumptions on changes in August runoff is even higher (−94% to −5%). The spread in RCM results accounts for 20–50% of the overall uncertainty in modeled discharge. Initial ice thickness, the amount and spatial distribution of winter snow and the glacier retreat model have the largest effect on the projections, whereas the RCM downscaling procedure, calibration data quality and the melt model (energy balance vs. degree-day approach) are of secondary importance.

1. Introduction

Ongoing and future climate change has major impact on alpine environments (e.g., Beniston, 2003). The potential loss of a substantial fraction of glacier ice volume until the end of this century will significantly alter the runoff characteristics of mountainous drainage basins (e.g., Braun et al., 2000; Barnett et al., 2005; Huss, 2011). Due to a seasonal shortage of water supply, downstream impacts of changes in the cryosphere might be considerable in terms of irrigation for agriculture, hydropower production, river transportation and ecology (Xu et al., 2009; Immerzeel et al., 2010; Kaser et al., 2010; Viviroli et al., 2011).

Numerous model studies for a wide range of climatic settings have been performed, estimating future trends in the hydrology of glacierized basins (e.g., Juen et al., 2007; Stahl et al., 2008; Weber et al., 2010; Hagg et al., 2013; Bavay et al., 2013; Ragettli et al., 2013). As a robust result, a shift in the runoff regime and a decrease in melting season discharge is found on the long run. However, an integrative uncertainty assessment of modeled future runoff from high-mountain catchments has not been performed to date.

The uncertainty in projected runoff is the combined effect of the spread in climate model results, the downscaling procedure, input data quality, as well as simplifications and poorly understood feedbacks in the modeling of glacier change and runoff. Although the individual uncertainties might cancel each other out, some parameterizations in the impact models might lead to a systematic over- or underestimation of future runoff, and thus require a careful evaluation. Knowledge about the integrated uncertainties is vital for making runoff projections useful in terms of adaptations in the water resource management.

Several individual components of the uncertainty in glacier runoff projections have recently been assessed. The impact of differences in air temperature and precipitation trends projected by Regional Climate Models (RCMs) or Global Circulation Models (GCMs) on the runoff regime of glacierized catchments was addressed in different regions (e.g., Stahl et al., 2008; Farinotti et al., 2012; Lutz et al., 2013; Ragettli et al., 2013). Dedicated studies have investigated the effect of climate model data downscaling procedures on calculated glacier mass balance (e.g., Radić and Hock, 2006; Kotlarski et al., 2010; Salzmann et al., 2012), and the

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field data requirements for an unambiguous calibration of hydrological models (Konz and Seibert, 2010; Schaefli and Huss, 2011). It has been recognized that the estimate of the initial glacier ice volume (Gabbi et al., 2012), and the approach to calculate glacier geometry change have a strong impact on calculated future glacier area and runoff (Huss et al., 2010b; Linsbauer et al., 2013). Many studies have focused on uncertainties in modeling of snow and ice melt based on the surface energy balance or temperature-index models (e.g., Klok and Oerlemans, 2004; Hock, 2005; Pellicciotti et al., 2005; Kobierska et al., 2013). Other factors such as the effect of the spatial snow accumulation distribution, and changes in debris-covered glacier surfaces on modeled discharge have not yet been specifically addressed by glacio-hydrological studies to our knowledge.

This paper aims at a detailed assessment of the major uncertainties in the modeling of future runoff from glacierized drainage basins, and quantifies potential uncertainty ranges based on an extensive set of model experiments. This allows identifying the factors and processes that are the least constrained by state-of-the-art glacio-hydrological model approaches and are most influential for the overall uncertainty in 21st century runoff projections. Our study is focused on the high-alpine catchment of Findelengletscher, Swiss Alps, for which a wealth of data on glacier mass balance and discharge over several decades is available. The basin thus represents an ideal test site for this comprehensive modeling study.

2. Study site and data

2.1. Geographical setting

Findelengletscher is a large temperate valley glacier in the southern Swiss Alps (46°00′N, 7°52′E). The region is characterized by glacier equilibrium line altitudes of around 3300 m a.s.l., being among the highest in the Alps (Maisch et al., 2000). The catchment of the hydrological station ranges from 2484 to 4173 m a.s.l., and has an area of 21.2 km^2 (Fig. 1). The basin is located in the headwaters of the Rhone River and was 74% glacierized in 2010, leading to a distinctly glacial runoff regime. Findelengletscher (13.0 km^2 in 2010) occupies the largest part of the watershed. Adlergletscher (2.0 km^2) and a few smaller glaciers make up for the rest of the glacierization (Fig. 1).

2.2. Studies on Findelengletscher

Over the last years, considerable knowledge about glaciological and hydrological processes and changes in the basin of Findelengletscher has been accumulated representing a starting point for this study. Machguth et al. (2006a) and Sold et al. (2013) investigated the spatial distribution of winter snow on Findelengletscher. Long-term series of glacier mass balance since 1900 were derived by Huss et al. (2010a). Several authors have addressed the future hydrology of the catchment. Farinotti et al. (2012) calculated glacier retreat and runoff over the 21st century using ten RCMs of the ENSEMBLES project (van der Linden and Mitchell, 2009). Uhlmann et al. (2013a) and Uhlmann et al. (2013b) calibrated a hydrological model to discharge data and performed a model run until 2100 using results of one RCM from the PRUDENCE project (Christensen and Christensen, 2007).

2.3. Field data

A mass balance monitoring program is maintained on Findelen- and Adlergletscher since 2004 (Machguth, 2008). Extrapolation of mass balance measured at a network of 13 stakes and 2 snow pits (Fig. 1) over the glacier yields the annual mass budget of Findelengletscher, as well as the altitudinal distribution of melt and accumulation. Winter balance is determined since 2009 by 5–10 snow pits and 400–700 manual snow probings per survey, distributed over the entire elevation range. The monitoring of snow accumulation distribution is further supported by helicopter-borne ground-penetrating radar (GPR) since 2010 providing snow depth on several tens of kilometers of continuous tracks (Sold et al., 2013).

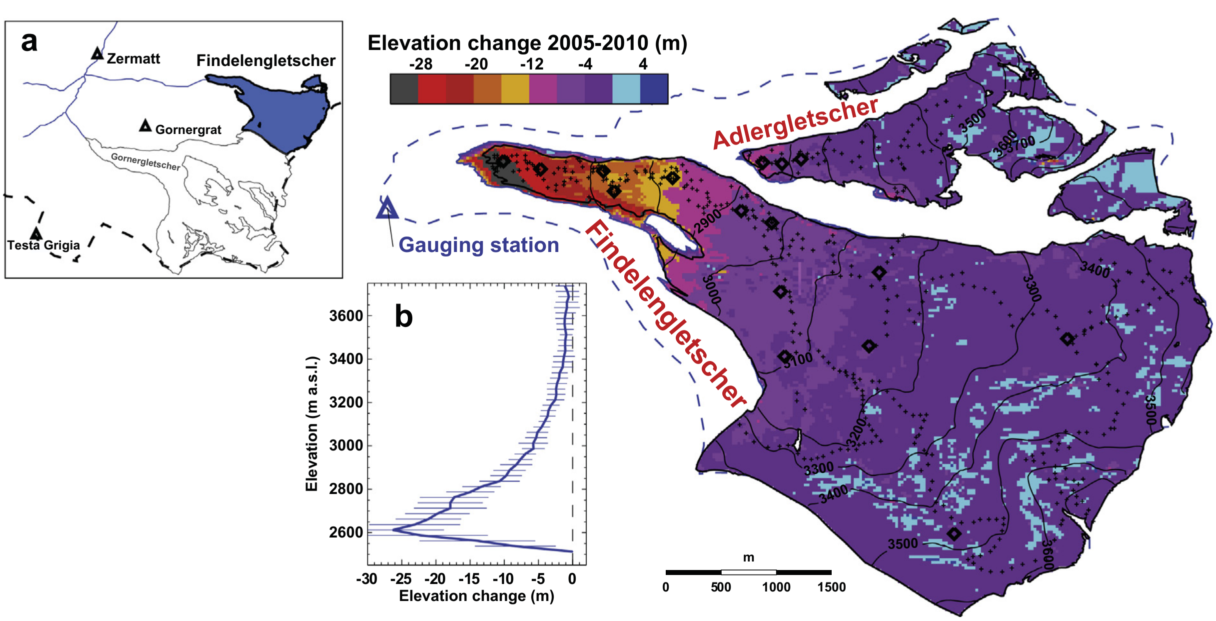

Fig. 1. Recent changes in the geometry of Findelengletscher. Colours show glacier surface elevation changes between October 2005 and September 2010 based on a comparison of two DEMs (Joerg et al., 2012). Stakes and snow pits for the measurement of annual mass balance are depicted with diamonds, snow probings realized in April 2010 are indicated (crosses). The location of weather stations around the study site is given in inset (a). Inset (b) provides the altitudinal distribution of observed surface elevation change. The variability (±2 standard deviations) within each band is shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)